INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING APPROACH TO DEVELOPMENT OF LIGHTWEIGHT 3GAHSS VEHICLE ASSEMBLY

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United States Automotive Materials Partnership

June 6, 2017

Project ID LM080

Overview

Timeline

- Project Start Date: February 1, 2013
- Project End Date: March 31, 2017
- Percent Complete: 100%

Budget

- Total Project Funding
  - DOE Share: $6,000,000
  - Contractor Share: $2,571,253
- Funding received in FY16: $1,499,441
- Funding for FY17:
  - DOE Share: $1,343,136
  - Contractor Share: $575,630

Barriers

A. ***Cost.*** Prohibitively high cost of finished materials is the greatest single barrier to the market viability of advanced lightweight materials for automotive vehicle applications

B. ***Performance.*** Low cost materials needed to **achieve performance** objectives may not exist today

C. ***Predictive modeling tools.*** Predictive tools that **will guide low** cost manufacturing of lightweight automotive structures would reduce the risk of developing new materials.

Participants

Universities / National Labs	Industry	Consortiums
Brown University	FCA US LLC	Auto/Steel Partnership
Clemson University	Ford Motor Company	United States Automotive Materials Partnership
Colorado School of Mines	General Motors Company	
Pacific Northwest National Lab	ArcelorMittal	
Ohio State University	AK Steel Corporation	
University of Illinois at Urbana-Champaign	Nucor Steel Corporation	

Relevance

Project Goal:

- To reduce the lead time in developing and applying lightweight third generation advanced high strength steel (3GAHSS) by integrating material models of different length scales into an Integrated Computational Materials Engineering (ICME) model

Predictive Modeling Tools

- Primary deliverable: An **ICME Model** capable of predicting 3GAHSS flow behavior and fracture to:
  - Reduce time and cost to develop and validate new 3GAHSS alloys
  - Improve manufacturability of the 3GAHSS automotive components with improved forming simulations
  - Facilitate implementation of 3GAHSS alloys in automotive structures through improved performance modeling
  - Estimate the cost of 3GAHSS components and assemblies

Cost Barrier:

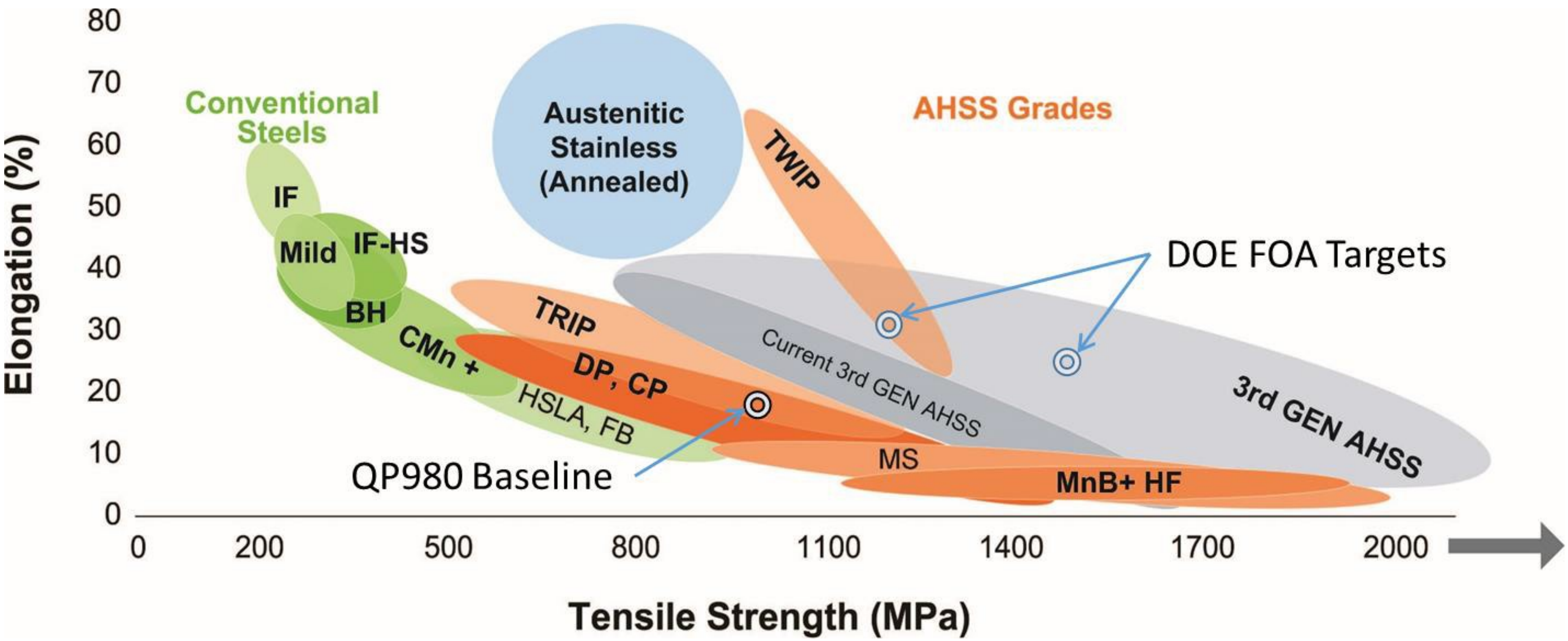
- Will demonstrate the ability to produce 3GAHSS materials at no more than **$3.18 cost per pound weight saved.**

Performance Barrier

- Will demonstrate the viability of 3GAHSS steels to meet vehicle performance requirements while reducing vehicle assembly weight (**35% lighter)**

[1]Light-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials, Workshop, pp12, 2013, US DOE VTO

Relevance



- There were no commercially available 3GAHSS <u>that met the DOE FOA</u> targets at the start of this project.
- The project had to make 3GAHSS for material model calibration and validation.

Milestone Flow Chart

(transition from baseline QP980 steel to New 3GAHSS steels)

No.	Project Milestone	Planned Completion Date	Actual Completion Date
1	Selection of Body Structure components/subassembly and identification of baseline materials	9/30/2013	9/15/2013
2	Meso-scale Computational Predictions: Validated meso-scale computational predictions from tasks 2.5, 2.6 and 2.7.	1/31/2015	1/30/2015
3	Macroscopic Constitutive Models: Develop and validate macroscopic constitutive models for deformation and fracture	1/31/2016	Partially Complete 1/31/2016
4	Initial Forming Model:	1/31/2016	1/19/2016
5	3GAHSS Forming Model	1/31/2017	1/31/2017
6	Estimated Joint Properties	7/31/2016	7/31/2016
7	Baseline Assembly Design Defined	1/31/2014	1/16/2014
8	Optimized Design	3/31/2017	3/31/2017
9	ICME Model	3/31/2017	3/31/2017
10	Data Model	3/31/2017	3/31/2017
11	Technical Cost Model	3/31/2017	3/31/2017

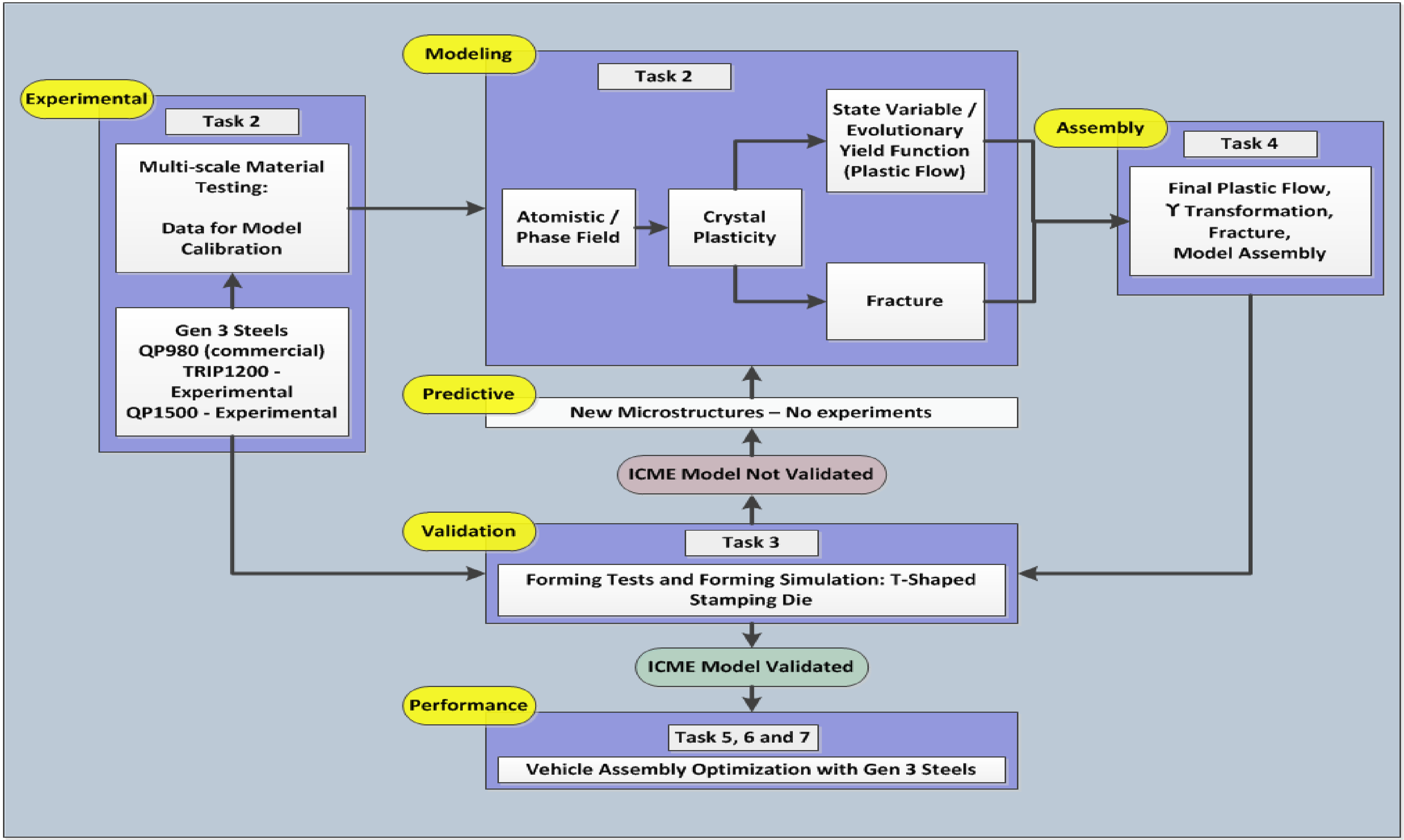
Approach/Strategy

- A highly collaborative project ***under experienced USAMP consortium and A/SP leadership***, was created:
  - **OEM members:** Responsible for system requirements, acceptance criteria and performance targets in the design of 3GAHSS components and automotive assemblies.
  - **A/SP steel companies**: Responsible for design, manufacture and testing of new 3GAHSS alloys.
  - **Universities and national laboratory:** Responsible for the development and validation of ICME material models using a combined experimental and computational approach.

Technical Task Outline

- **Task 2 'Model Development'**: Characterize baseline and 3GAHSS steels to provide constitutive material property information to calibrate material models
- **Task 3 'Forming'**: Develop and calibrate 3GAHSS forming models
- **Task 4 'Assembly'**: Assemble 3GAHSS material and forming models
- **Task 5 'Design Optimization'**: Substitute 3GAHSS material cards into the side structure design; determine mass savings and performance impact
- **Task 6 'ICME Model'**: Develop and ICME Model with a User Guide and Data Model
- **Task 7 'Technical Cost Model'**: Assess and compare the manufacturing cost of an AHSS baseline and 3GAHSS automotive side-structure assembly.

Approach/Strategy



Technical Accomplishments and Progress

The development of NEW 3GAHSS for model calibration:

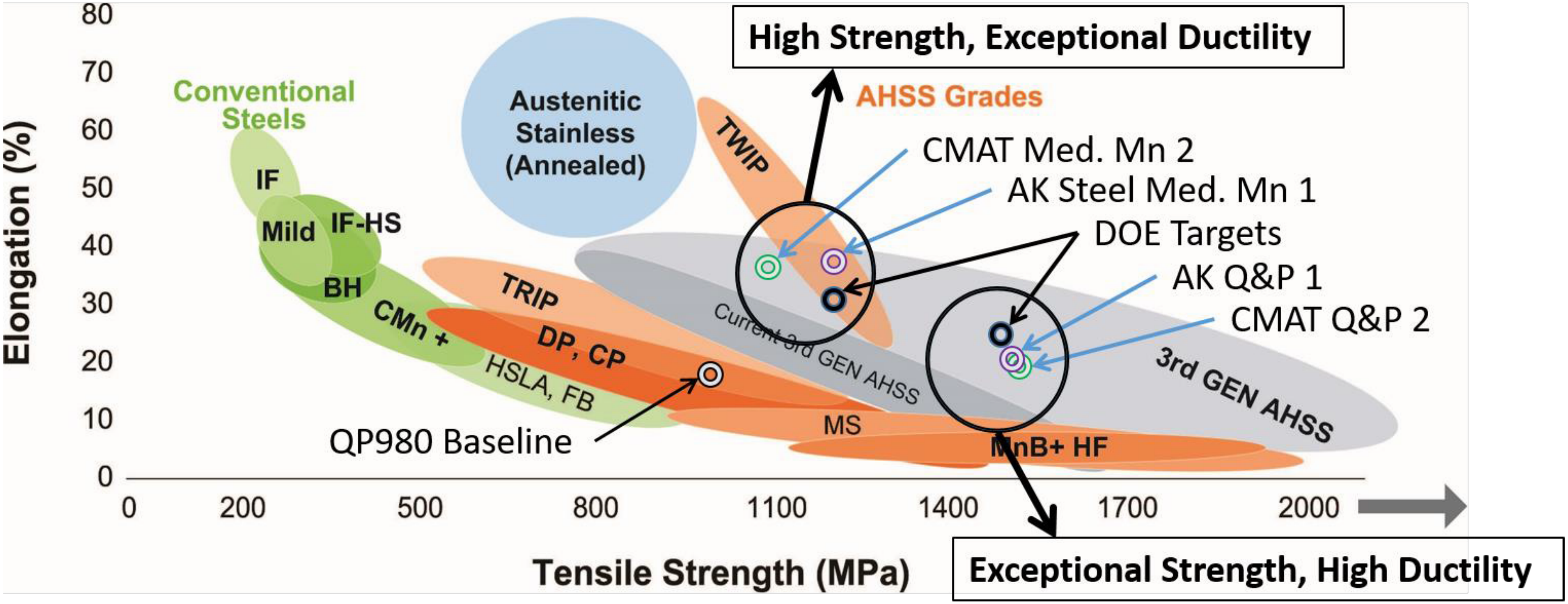
- Colorado School of Mines provided two recipes along two steel processing paths to meet the two DOE FOA targets
  - Transformation Induced Plasticity (TRIP) Path - ~10 wt.% Mn (medium) Steel
  - Quench and Partitioned (Q&P) - ~3 wt.% Mn Steel
- AK Steel validated the two recipes by creating approximately 1 mm thick by 125 cm wide x 1,500 cm long strips.
- CANMETMaterials (CMAT) scaled up the recipes by producing wider strips, which were approximately 1.1 mm thick by 215 cm wide by 1,500 cm long.
  - McMaster University used an annealing simulator to heat treat the Q&P steel.

Material	Rolling Mill	Heat Treater	Sequence	Material Designation
		AK Steel		
10% Mn TRIP Steel	AK Steel	AK Steel	Hydrogen Annealed	AK Steel Medium Mn 1.1
	AK Steel	AK Steel	Nitrogen Annealed	AK Steel Medium Mn 1.2
	AK Steel	CSM	Nitrogen Annealed	AK Steel Medium Mn 1.3
3% Mn Q&P Steel	AK Steel	AK Steel		AK Steel Q&P 1.1
	AK Steel	CSM		AK Steel Q&P 1.2
		CANMETMaterials		
10% Mn TRIP Steel	CMAT	CMAT	Phase 1	CMAT Medium Mn 2.1
	CMAT	CMAT	Phase 2	CMAT Medium Mn 2.2
3% Mn Q&P Steel	CMAT	CSM	Phase 1	CMAT Q&P 2.1
	CMAT	McMaster University	Phase 2	CMAT Q&P 2.2

NEW 3GAHSS Steels Created with project nomenclature
- Rolling Mill
- Heat Treater
- Sequence
- Steel Designation

Technical Accomplishments and Progress

The production of the NEW 3GAHSS steels a significant project achievement especially considering the proximity of mechanical properties with the DOE targets.



Steel Alloy	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Total Elongation	Uniform Elongation
High Strength, Exceptional Ductility	≥ 800	≥ 1,200	≥ 30%	≥ 20%
AK Steel Medium Mn 1.2	750	1,200	37%	34%
CMAT Medium Mn 2.1	693	1,042	35%	Not Measured
Exceptional Strength, High Ductility Steel	≥ 1,200	≥ 1,500	≥ 25%	≥ 8%
AK Steel Q&P 1.2	830	1,532	20%	Not Measured
CMAT Q&P 2.2 (McMaster)	1,218	1,538	20%	15%

Color Code:			
	TARGET	BELOW TARGET	MET TARGET

Technical Accomplishments and Progress

Task 2: Material Model Development and Validation

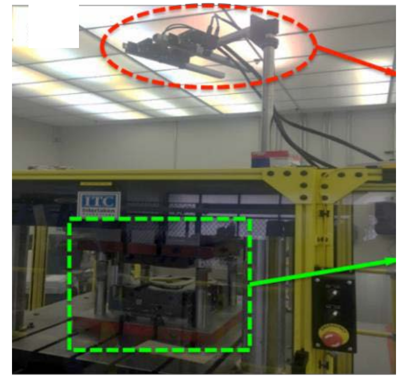
- Characterized 3GAHSS steels for microstructure, mechanical properties (quasi-static and rapid strain rate), and forming limit diagrams.
  - Developed a three dimensional (3D) representative volume element (RVE) for both 3GAHSS using DREAM 3D©
- Developed and calibrated the crystal plasticity and state variable models for both the baseline QP980 steel and the 3GAHSS
- Assembled crystal plasticity model (CPM) and state variable model (SVM)
  - Validated the output (material cards) of the assembled material models against the experimentally derived flow curves (quasi-static)
  - Added shell finite element capability to better support design optimization
- Developed a baseline QP980 and 3GAHSS fracture models
- Developed a new experimental procedure to measure retained austenite as a function of strain and strain path using digital image correlation and Argonne National Laboratory's Synchrotron High Energy X-Ray Diffraction.
  - Material cards were developed to include phase transformation as a function of strain

Task 2: Milestones			
Number	**Milestone Title**	**Milestone Description**	**Delivery Date**
2	Meso-Scale Model	Validated meso-scale computational predictions	Jan. 31, 2015
3	Macroscopic Constitutive Models	Develop and validate macroscopic constitutive models for deformation and fracture	Jan. 31, 2016

Technical Accomplishments and Progress

Task 3: Forming Simulation and Validation

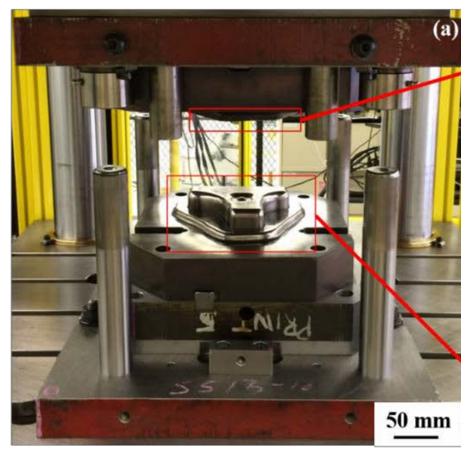
- Designed and built a T-Component Die for forming trials and model validation
- Simulated and produced T-Components from QP980 and 3GAHSS materials
  - Blanks were gridded, formed into T-Components at 1 mm/s, strains, and measured with DIC.
  - Coupons were excised from select regions based on strain path and tested at ANL to assess the volume of retained austenite as a function of strain path.

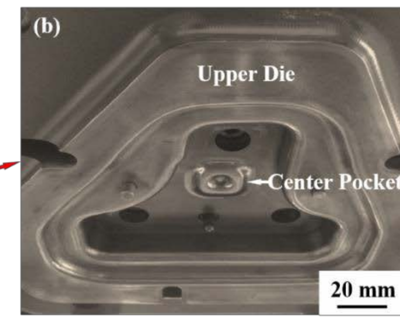


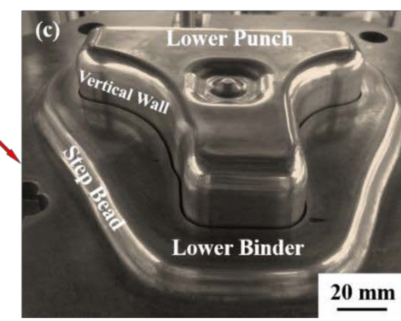
Three camera DIC system

T-Component Die Set (see below)

ICME Model Validation: T-shaped Stamping Die



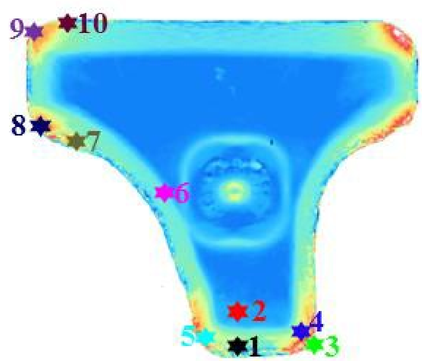


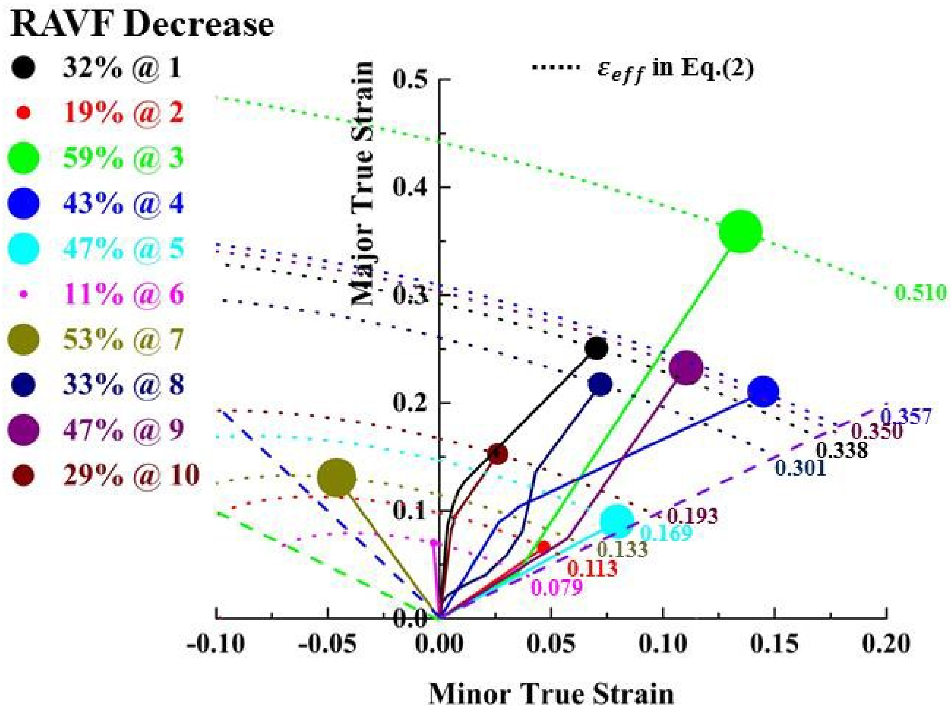


Task 3: Milestones			
Number	**Milestone Title**	**Milestone Description**	**Delivery Date**
4	Initial Forming Model	Component based forming model calibrated to the baseline material	Jan. 31, 2016
3	3GAHSS Forming Model	Component based forming model calibrated to 3GAHSS materials	Mar. 31, 2017

Technical Accomplishments and Progress

Task 3: Forming Simulation and Validation – CMAT Med. Mn. 2.1 (10 wt.% Mn TRIP Steel)

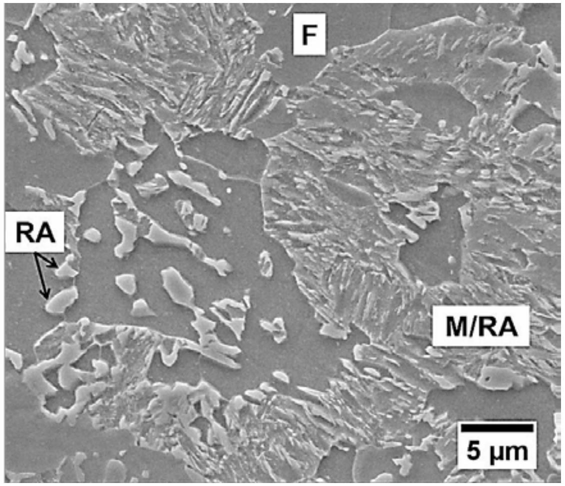




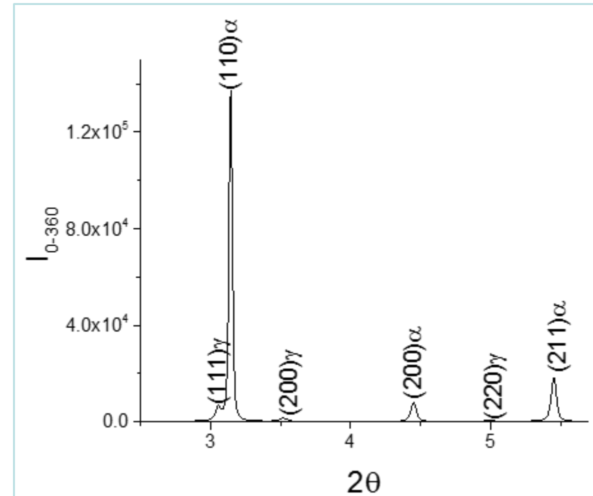
For an equivalent effective strain, the volume fraction of retained austenite can vary by strain path.

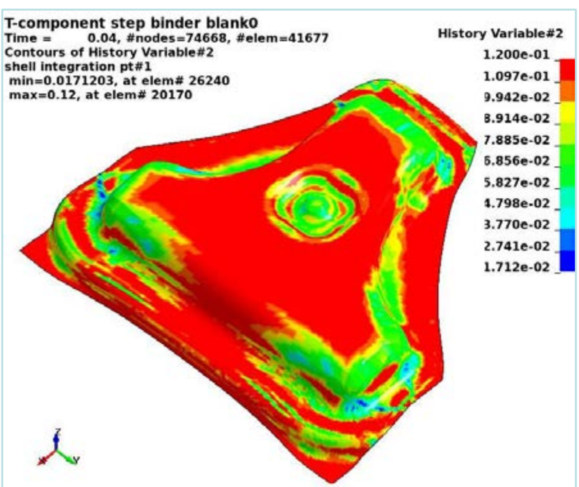
Technical Accomplishments and Progress

ICME Model Validation: QP980 Baseline Steel



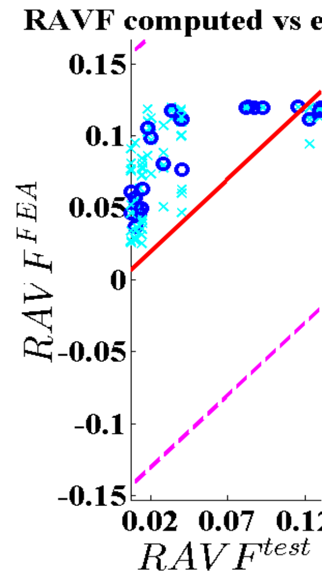
T-shaped stamping component with test coupons extracted





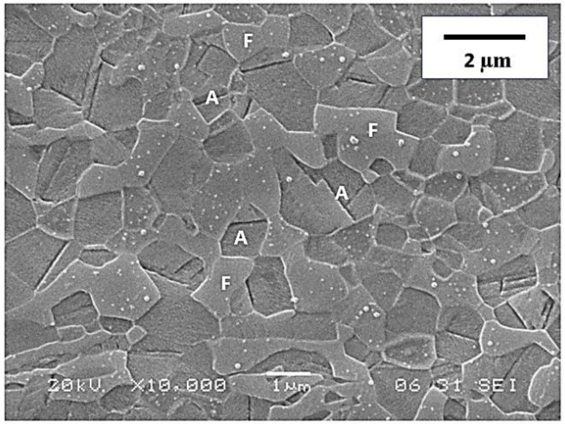
RAVF for QP980 T-shaped stamping obtained from ICME simulation

RAVF comparison: The cyan crosses show the 5 individual readings from FE for every coupon while the blue circles represent their mean. the dashed magenta lines represent $\pm$0.15 tolerances

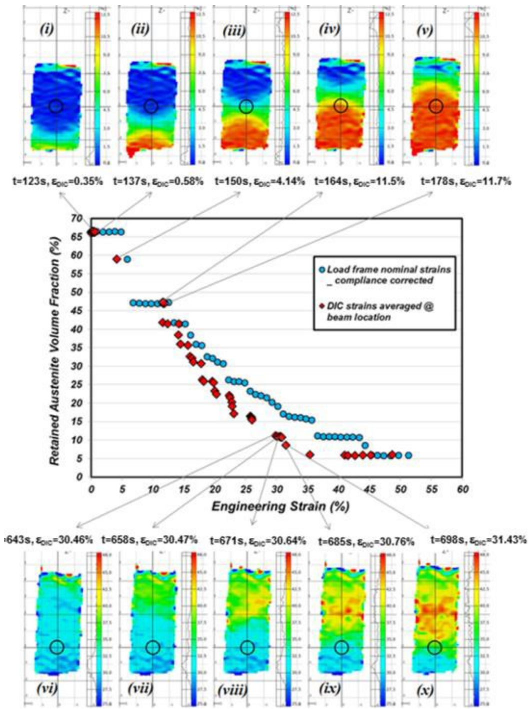


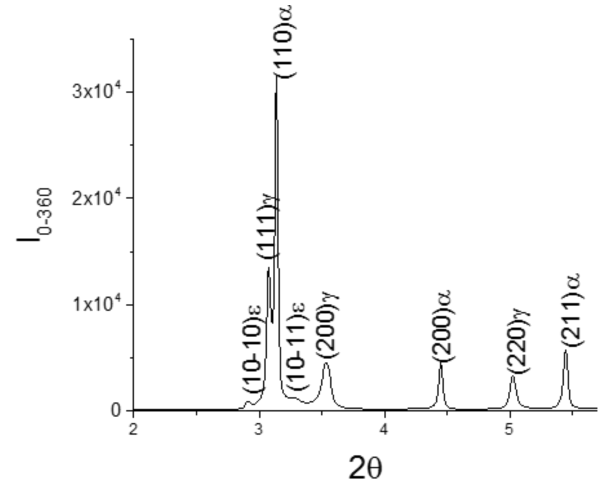
Technical Accomplishments and Progress

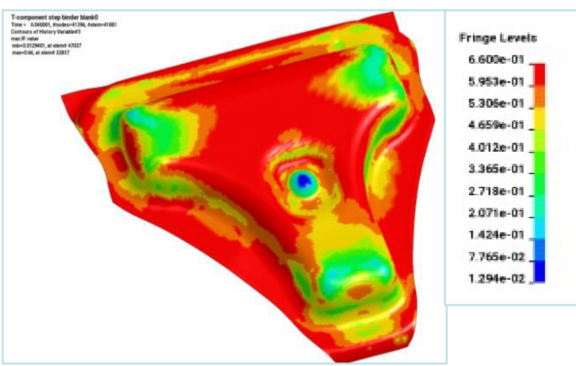
ICME Model Validation: CMAT Medium Mn 2.1 (10 wt. % Mn) TRIP Steel



A = Austenite (γ), 66%; F = Ferrite (α)

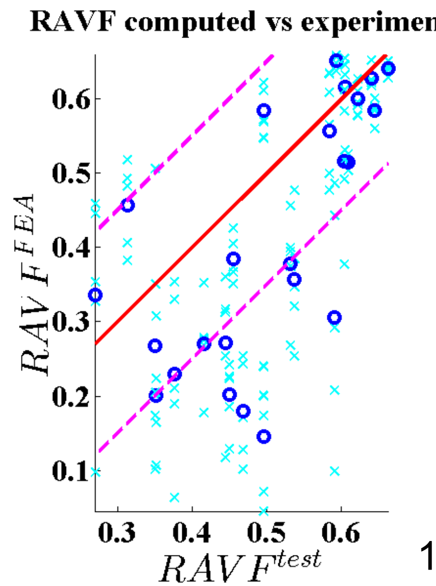






RAVF for Med. Mn T-shaped stamping obtained from ICME simulation

RAVF comparison: The cyan crosses show the 5 individual readings from FE for every coupon while the blue circles represent their mean. the dashed magenta lines represent ±0.15 tolerances



Technical Accomplishments and Progress

Task 5: Design Optimization

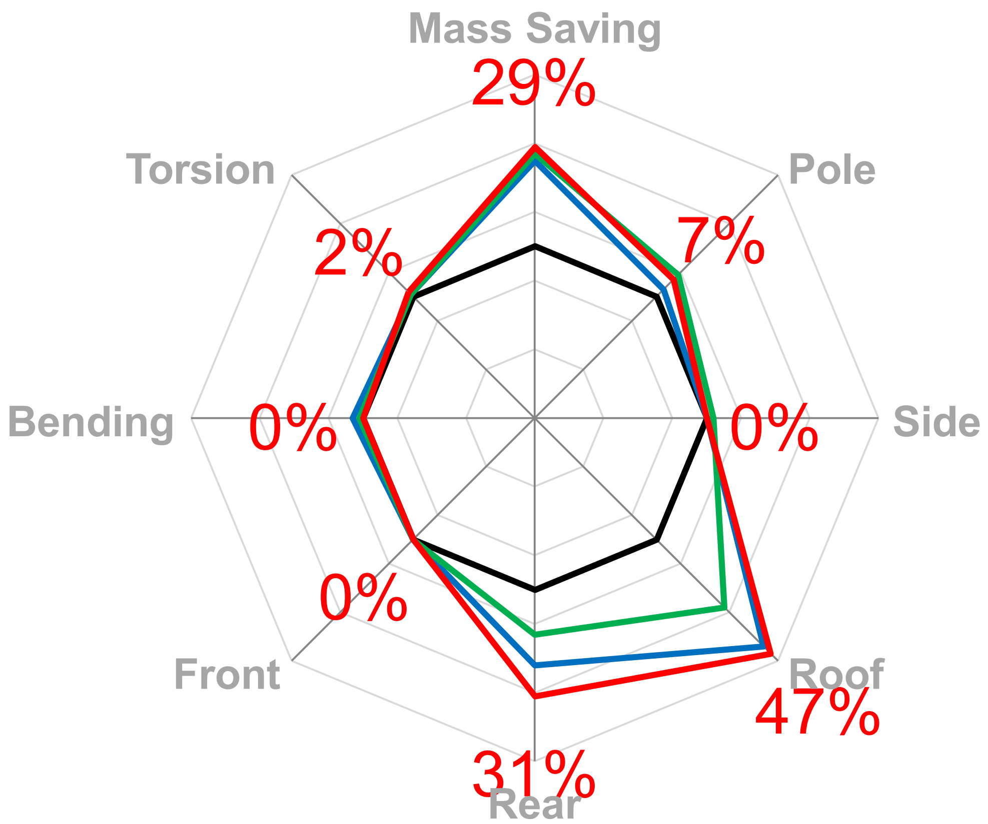
- Selected the side-structure sub-assembly from a 2008 MY sedan
  - Developed the bill of materials and defined the performance requirements for the side structure
- Substituted the two 3GAHSS material cards for all 3GAHSS components in the side structure design
- Developed the following key design iterations
  - Final design iteration #9 was performed at the NREL High Performance Computing Center

Design Iteration #	Crash Neutral	Stiffness Neutral	Mass Savings (Target 35%)	Optimization Strategy			Notes
				Thickness Opt.	Part Consolidation	Design Opt.	
3	Yes	No	35.60%	Yes	Yes	No	Met DOE Mass Savings Target but did not meet all performance requirements
7	Yes	Yes	19%	Yes	Yes	No	Met all performance requirements but did not meet DOE Mass Savings Target but did not meet all performance requirements
9	Yes	Yes	25%	Yes	Yes	Yes	Began shape/topology optimization
9+	Yes	Yes	29%	Yes	Yes	Yes	Final Design using NREL HPC

Task 3: Milestones		
Number	**Milestone Title**	**Delivery Date**
1	Selection of Body Structure components/subassembly and identification of baseline materials	Sept. 30, 2013
6	Estimated Joint Properties	Jul. 31, 2016
7	Baseline Assembly Design Defined	Jan. 31, 2014
8	Optimized Design	Mar. 31, 2017

Technical Accomplishments and Progress

Task 5: Design Optimization



Side Structure Subassembly
32 Components per side

Side Structure Subassembly Mass
- Original AHSS Design: …………………………………… ~ 94 Kg.
- Iteration #9 3GAHSS Design (Med. Mn. and QP1500): ... 67.5 Kg.

Mass savings: ~ 27 Kg. (~29%)

Technical Accomplishments and Progress

Task 4 / 6: Assembly and Integration

- USAMP / NIST CRADA to use the DSpace Data Repository for the storage and retrieval of project data – DATA MODEL
  - Developed a data ontology
  - Currently uploading project data
- Developed an 3GAHSS ICME Model
  - Framework developed using LS-OPT
  - Implemented model in commercial LS-DYNA Code
  - Wrote a user guide

Task 7: Technical Cost Model

- Developed a technical cost model for the side-structure
  - Baseline Side-Structure cost: (*data not available at time of print*)
  - 3GAHSS Side-Structure cost: (*data not available at time of print*)

Task 6: Milestones		
Number	**Milestone Title**	**Delivery Date**
9	ICME Model	Mar. 31, 2017
10	Data Model	Mar. 31, 2017
Task 7: Milestones		
Number	**Milestone Title**	**Delivery Date**
11	Technical Cost Model	Mar. 31, 2017

Response to Reviewers' Comments

Approach to performing the work - the degree to which technical barriers are addressed, the project is well-designed, feasible, and	
Reviewer Comment	**Project Response**
A Reviewer asked for the team to clarify Task 4 and make the presentation slides consistent	Task 4: Assembly was clarified as requested. Task 4 Assembly is focused on the assembly of material models and not manufacturing joining
A reviewer requested a description of the size of 3GAHSS heats made in this project	The experimental heats used to develop 3GAHSS process recipes were small (under 5 pounds) but the heats made at AK Steel were approximately 50 pounds and the heats made at CMAT were approximately 450 pounds
A reviewer suggested that the approach shown in Slide 10 of the 2014 presentation was too complicated	A simplified chart that covers all project tasks has been substituted in this presentation

Technical accomplishments and progress toward overall project and DOE goals – the degree to which progress has been made, measured against performance indicators and demonstrated progress toward DOE goals	
Reviewer Comment	**Project Response**
A reviewer requested an example of how characterization of QP980 could be used in formability modeling	The characterization of QP980, in terms of tensile and compression flow curves and forming limit diagrams, will provide constitutive mechanical property information from which material models (crystal plasticity, state variable, and evolutionary yield function) can be developed and validated. The models will include the transformation kinetics of retained austenite transforming to martensite as a function of strain. These multi-level physics models will be used in finite element simulation of manufacturing processes and component response to forming events (i.e. stretch, stretch bending, etc.)
A reviewer requested an update on progress to prediction uncertainty of the ICME models (goal is 15%) and a risk assessment as to whether the project team will be able to meet that goal	PNNL calibrated the state variable model using QP980 experimental data and was able to predict the flow curve of QP980 in good agreement with experimental results. The team expects that similar results will follow with the exceptional strength, high ductility steel which uses a similar quench and partitioning process. No estimate is currently available for the high strength, exceptional ductility material as there are currently no models available that account for austenite transformation during deformation and that account for the competing deformation mechanisms of twinning and transformation induced plasticity

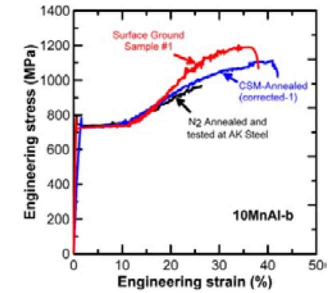
Response to Reviewers' Comments

Collaboration and coordination with other institutions	
Reviewer Comment	**Project Response**
The reviewer asked whether foreign participation was considered	The emphasis on the project was to maximize domestic participation since the project is funded by the United States Department of Energy. However, CMAT has been contracted to make experimental 3GAHSS coupons using less than 2% of the total project funds
A reviewer commented that given the funding executed thus far that there may have been some initial hiccups in operationalizing the planned communication	•There were some delays in finalizing agreements with some of the sub-recipients and vendors that delayed the start of work but did not impact the timing of project milestones.

Proposed future research – the degree to which the project has effectively planned its future work in a logical manner by incorporating appropriate decision points, considering barriers to the realization of the proposed technology, and, when sensible, mitigating risk by providing alternate development pathways	
Reviewer Comment	**Project Response**
A reviewer requested clarification on the technical barriers expected in future work, a risk mitigation plan and a slide focusing on technical details	Slides 28 and 29 discussing risks were added to the reviewer only section
A reviewer requested revisiting the approach	The project team continues to revisit the approach in Project Coordination and Integration Team meetings to better clarify the approach at the sub-task level and to insure integration at the task level. The Approach/Strategy section was modified to better show the high-level approach and project organization

Collaboration and Coordination with Other Institutions

- Project participants: (see Slide 2)
  - Five universities
  - One national laboratory
  - Four steel companies
  - Three automotive OEMs
  - Two engineering firms.

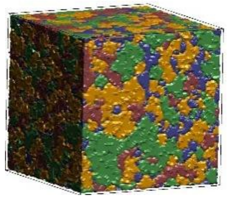


AK Steel Med. Mn 1 Flow Curve (3GAHSS)

- Due to the number of participants, highly leveraged cross-functional task teams have been formed.
  - Examples of integration through collaboration:
    - OSU / BU / CU: 3D RVEs
    - CU / PNNL / GM: HEXRD at ANL
    - A/SP / AK Steel / CSM / PNNL: 3GAHSS coupon creation
    - CU / OSU / PNNL / LSTC: Material model assembly
    - BU / CU / OSU / PNNL: Material model calibration
    - A/SP / GM / EDAG: Side structure baseline performance characterization
    - PNNL / Task 2: Use of PNNL SharePoint website for document storage

CMAT Hot Band Steel


Side-Structure Assembly


3D RVE simulation

Remaining Challenges and Barriers

ICME Model is Set up to Test Hypothetical Microstructures based upon Steels made in the project and the NIST data model

austenite martensite

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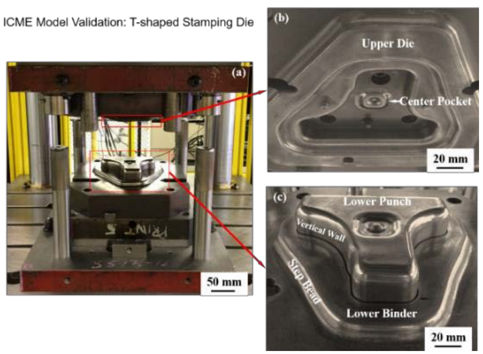
ICME Model Validation: T-shaped Stamping Die



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NIST
Material Measurement Laboratory
materialsdata.nist.gov

NIST Repositories → ICME Approach to Development of Lightweight 3GAHSS Vehicle Assembly

ICME Approach to Development of Lightweight 3GAHSS Vehicle Assembly

The goal of the program is to successfully demonstrate the applicability of Integrated Computational Materials Engineering (ICME) for the development and deployment of third generation advanced high strength steels (3GAHSS) for immediate weight reduction in passenger vehicles. The ICME approach will integrate results from well-established computational and experimental methodologies to develop a suite of material constitutive models (deformation and failure), manufacturing process and performance simulation modules, a properties database, as well as the computational environment linking them together for both performance prediction and material optimization. The project officially started on February 1, 2013. Currently, access to these data is restricted to the funded DOE participants in this GM-led project.

Sub-communities within this community

- Computational Methods
  Community focus on Computational Methods used in the ICME-3GAHSS
- Experimental Data

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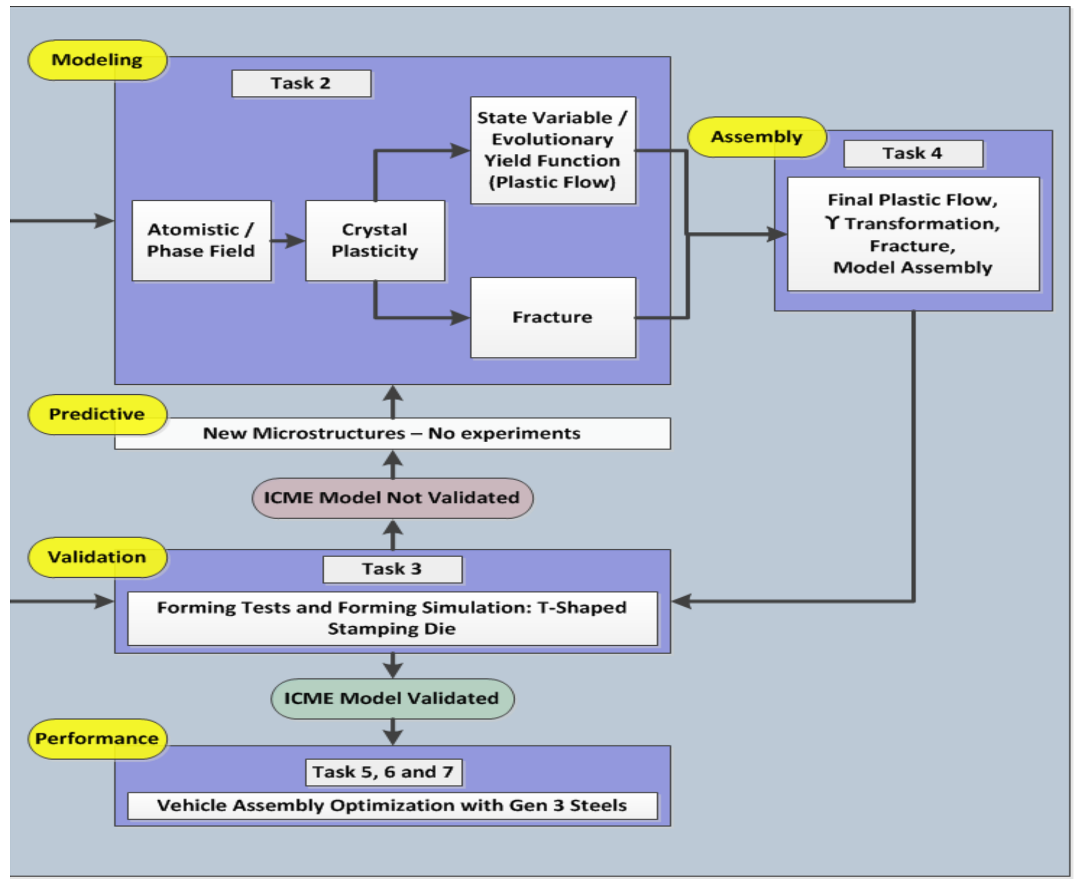


Remaining Challenges and Barriers

The ICME 3GAHSS project is complete!

The Project Team identified the following technical gaps that could yield improvements in 3GAHSS ICME Model applicability and accuracy.

- Inclusion of discrete dislocation dynamics in the crystal plasticity model
- Three dimensional representative volume elements that reflect processing history
- Ability to assess critical resolved shear stress for single crystals with grain sizes less than 2 microns
- Temperature / strain rate effects on austenite transformation
- Improved ability to predict component mechanical properties with respect to non-linear strain paths coupled with deformation induced phase transformation
- Development of comprehensive material cards that include transformation and rapid strain rate behavior
- Full integration of microstructural / phenomenological fracture models into ICME Model

Summary

Project Goal:

- To reduce the lead time in developing and applying lightweight third generation advanced high strength steel (3GAHSS) by integrating material models of different length scales into an Integrated Computational Materials Engineering (ICME) model

Result:

- A 3GAHSS ICME Model exists which has been calibrated for two 3GAHSS materials along two distinct steel processing pathways, 1) TRansformation Induced Plasticity (TRIP) and 2) Quench and Partitioned (Q&P).
- Two 3GAHSS steels were created in laboratory sized heats at AK Steel and scaled up to production-like heats at CANMET and McMaster University.

Project Objectives

- Identify, validate (within 15% of experiments) and assemble length scale material models for predicting 3GAHSS constitutive behavior for component forming and performance
- Optimize assembly design using ICME-predicted 3GAHSS model to be **35% lighter** and no more than **$3.18 cost per pound weight saved** to meet DOE VTO gaps and targets[1].

Result:

- ICME Model produced material cards are in agreement with experimental results for the baseline and 3GAHSS materials.
- The optimized 3GAHSS assembly design achieved a 29% mass savings versus the baseline AHSS design.
- Cost per pound of weight saved data not available at time of print.

Conclusions

The project did not meet all objectives but demonstrated:

- The potential to produce 3GAHSS materials with high ductility and strength using production-like equipment
- In the absence of a stiffness criteria, the ability to substitute 3GAHSS into a safety critical automotive subassembly and meet an aggressive 35% mass savings target while meeting or exceeding crash performance targets using 3GAHSS in a safety critical automotive sub-assembly
- The ability to substitute 3GAHSS into a safety critical automotive subassembly design, meet all performance criteria, including crash and stiffness, and achieve a 29% mass savings
- The ability to coordinate industry, academic and national lab resources to collaboratively develop a ICME Model using commercially available code.

DELIVERABLES:

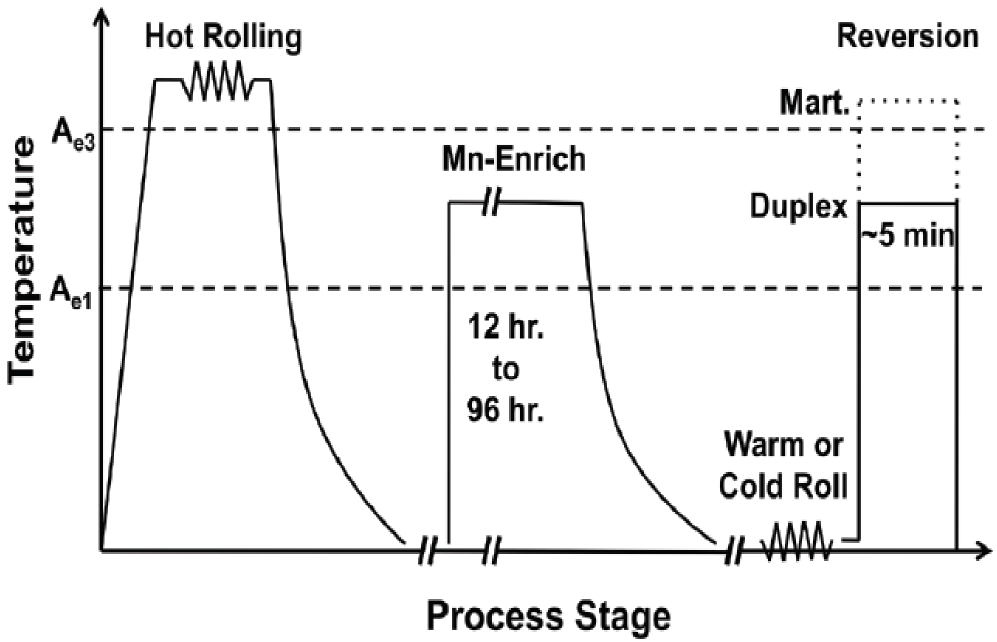
- Two validated 3GAHSS recipes
- Laboratory procedure for assessing in-situ transformation of retained austenite to martensite as a function of strain
- 3GAHSS ICME Model and User Guide
- 3GAHSS Technical Cost Model

Acknowledgement

This material is based upon work supported by the Department of Energy National Energy Technology Laboratory under Award Number No. DE-EE0005976.

Back-up Slides

New 3GAHSS - Medium Mn Steel



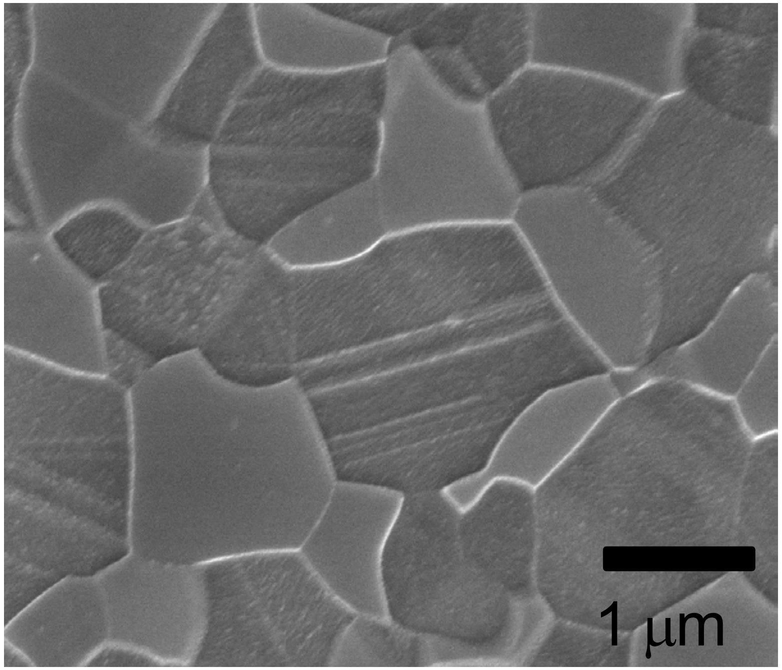
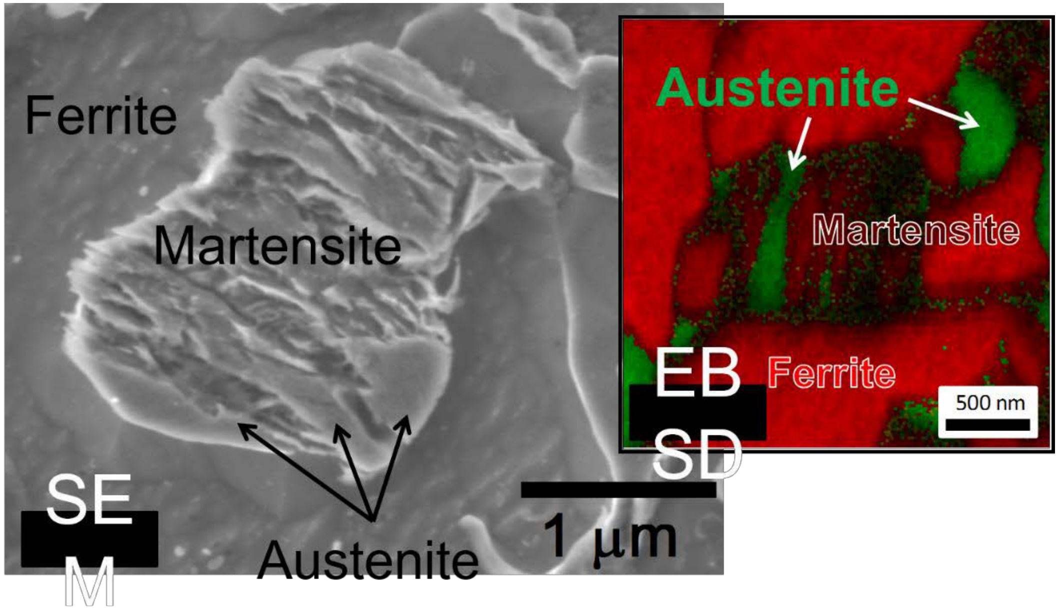
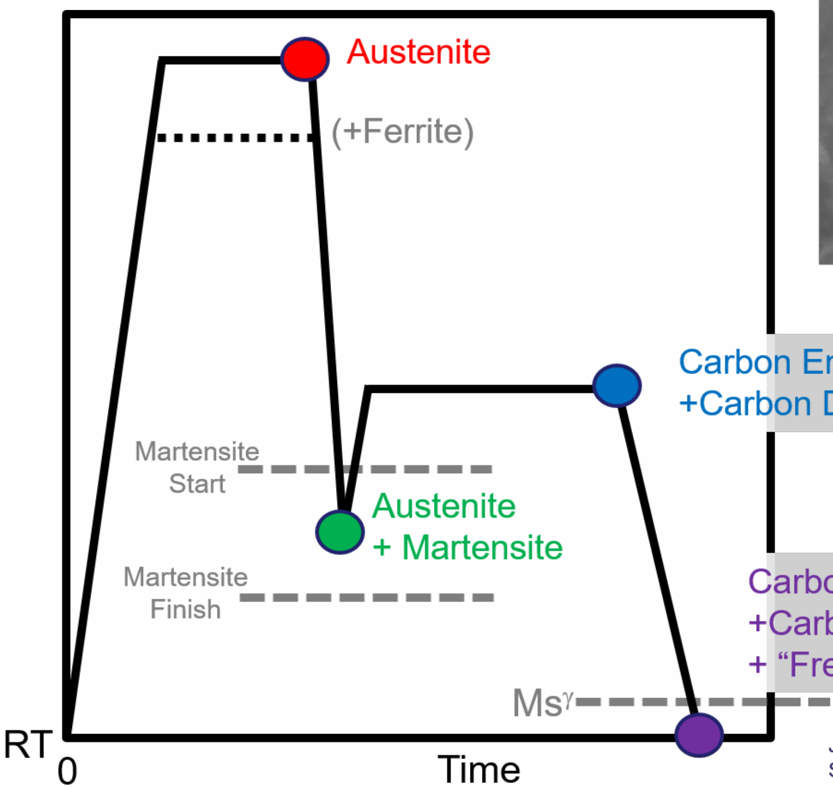


Image courtesy of Hyokyung Sung and Sharvan Kumar, School of Engineering, Brown University

P. Gibbs, Ph. D. Thesis, Colorado School of Mines, 2012
E. De Moor, D. K. Matlock, J. G. Speer, M. J. Merwin, Scripta Mater., 2011, 64 (2), 185
.

New 3GAHSS – Q&P Steel



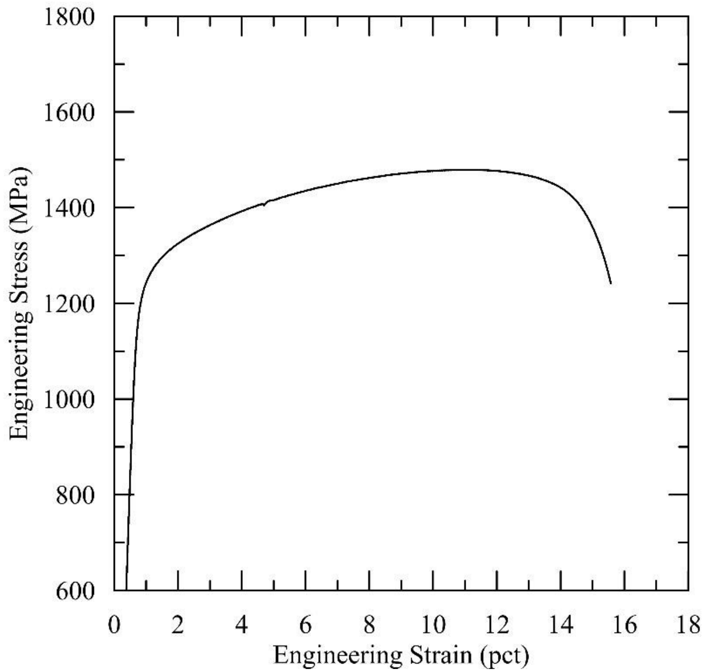


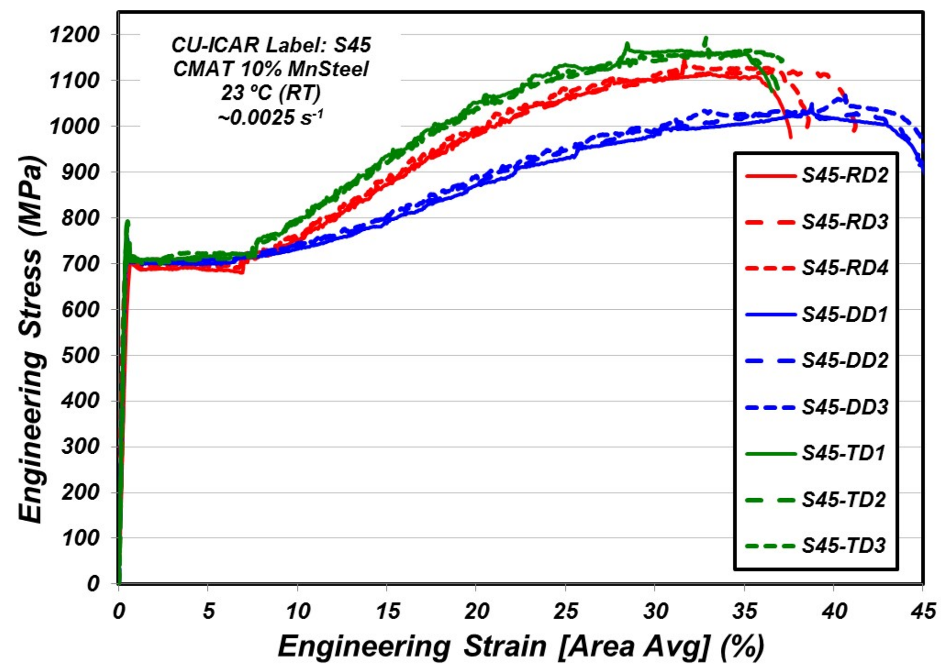
Carbon Enriched Austenite
+Carbon Depleted Martensite

Carbon Enriched Austenite
+Carbon Depleted Martensite
+ “Fresh” Martensite

J. Speer, D. K. Matlock, B. C. De Cooman, and J. G. Schroth, Acta Materialia, vol. 51, pp. 2611-2622, 2003.

New 3GAHSS – Flow Curves





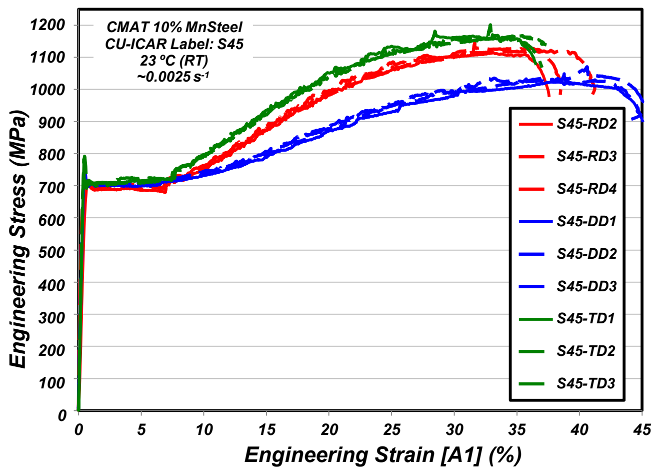
Stress Strain Curve for the CMAT Q&P 2.2 steel.

Courtesy of Colorado School of Mines

Stress Strain Curve for the CMAT Medium Mn 2.1 steel.

Courtesy of Clemson University

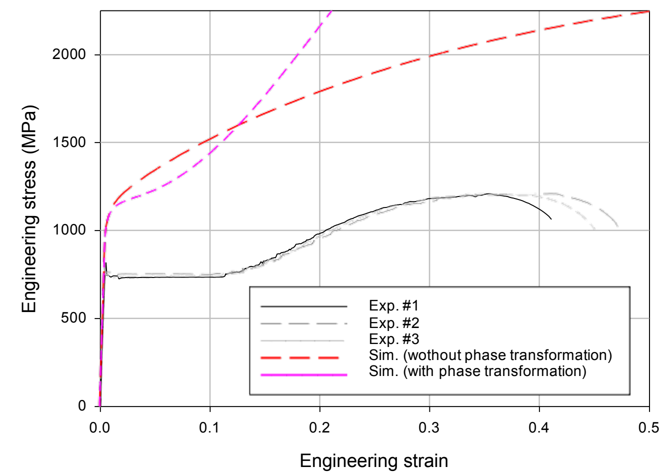
Crystal Plasticity Calibration

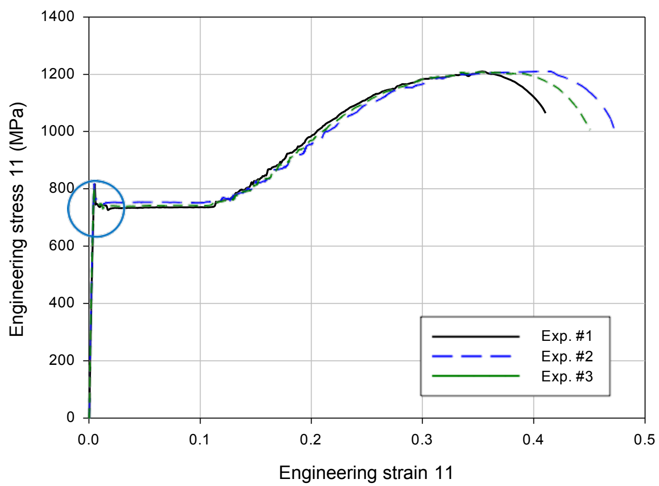


Experimental results for CMAT Medium Mn 2.1 Steel

Initial Crystal Plasticity Model prediction

- Incorrect yield strength
- Incorrect tensile strength
- Incorrect hardening

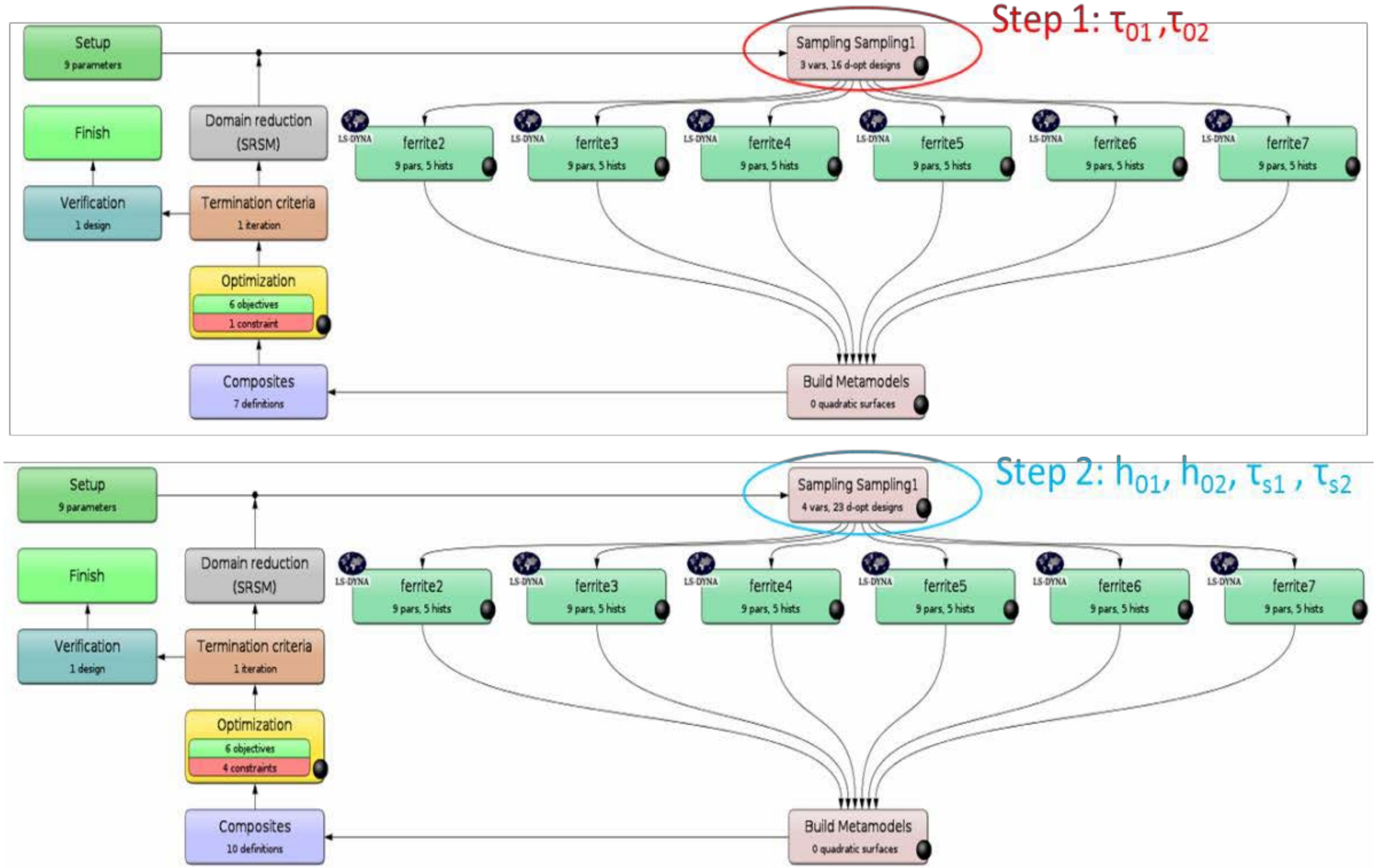




Current Crystal Plasticity Model Prediction for Medium Mn steel

- Added transformation kinetics
- Added polycrystalline capability
- Yield strength, tensile strength and hardening are now in good agreement with experimental results

ICME Model Excerpt (Courtesy of LSTC)



Innermost levels for Ferrite CP calibration. The top setup is the innermost level for calibrating the initial yield parameters while the bottom setup pertains to the calibration of hardening parameters.